PSC WHITE PAPER SERIES

ON DISTINGUISHING VARIOUS CONTRIBUTORS TO STRAY VOLTAGE FROM BOTH 'ON-FARM' AND 'OFF-FARM' SOURCES

BY
Mark A. Cook, Daniel M. Dasho, P.E., and Richard S. Reines
in consultation with Douglas J. Reinemann, PhD, Univ. of Wis.

Mar. 1994

INTRODUCTION

Stray Voltage is defined by the United States Department of Agriculture Handbook 696 (USDA, 1991) as a "difference in voltage measured between two surfaces that maybe contacted by an animal." When attempting to reduce any voltage levels in animal confinement facilities, it is absolutely essential that one must determine the level of contribution from either or both the "on-farm" (secondary) and the "off-farm" (primary) system sources. It is very important to recognize that both the primary and the secondary electrical systems are interactive and not independent of one another, although one source may dominate the contribution to any stray voltage found in an animal confinement area. In most cases however, some voltage is contributed to the animal contact area from each source. This paper presents a method of determining the portion of animal contact voltage contributed from the primary source and all secondary sources. This analysis method applies **only** when:

1. The secondary neutral is not isolated from the primary neutral and when,

2. There is a relative contribution from a single secondary service entrance and the primary system.

Most farms have multiple service entrances, e.g. one for the house and one for each outbuilding (barn(s), silo(s), machine shed(s) etc.). If a transformer supplies power to more than one service entrance, each service entrance must be tested independently without interference from other energized sources. Obviously because of its close proximity, the main area of concern is the service entrance supplying power directly to animal confinement areas. Because of the parallel nature of an on-farm distribution system, all other service entrances should be tested to determine their potential contribution to the voltage at the service entrance supplying power to the animal confinement area.

MEASUREMENT INSTRUMENTS

All measurements should be made with true-rms digital voltmeters with readings significant to at least two places. If more than one physical meter is used, care should be taken to assure that their readings agree when placed across the same two contact points. Simultaneous readings are obviously easier with several meters, but if several meters are not available, one must take sequential readings with a single meter until consistent voltage readings and ratios between readings at the various test points are obtained. A minimum elapse of time is a must between readings to assure consistent results.

Recording chart or computer-based digital meters may also be used for these tests if only one service entrance is operational during the recording period and care is taken to ensure that the various voltage readings are simultaneous. Some digital recording devices have "deviation" settings that will not record a change in any signal until that signal changes by more than the deviation setting amount. When using such recording meters, voltage readings are subject to the error of the magnitude of the deviation setting. It should be set as small as possible, but large enough to eliminate display 'jitter' from commonly occurring noise signals.

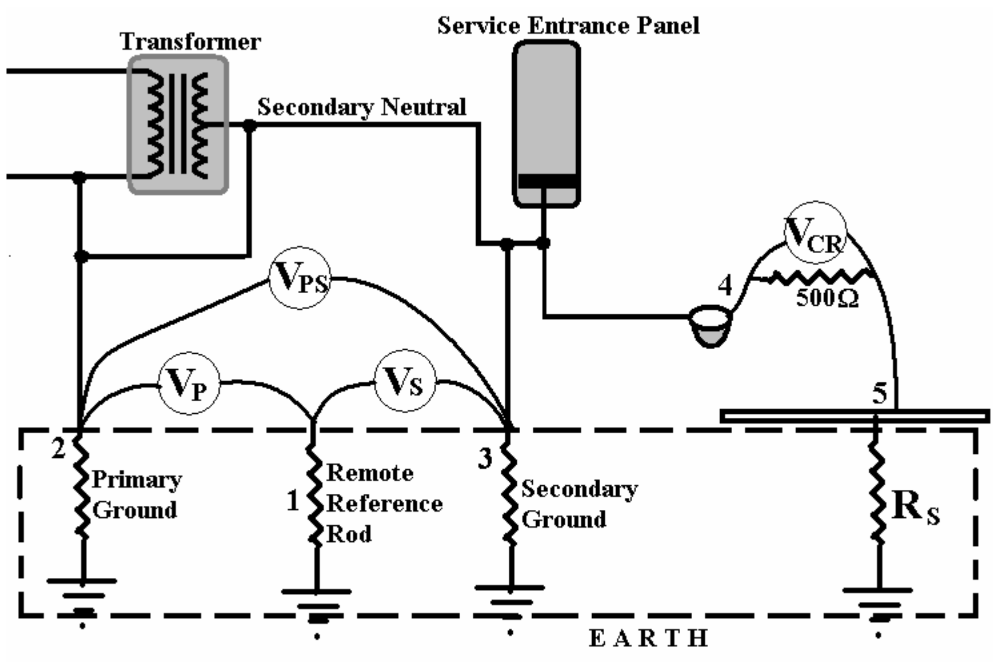

Figure 1: Measurement connections.

MEASUREMENT POINTS

Five (5) measurement points are required to perform this test (refer to Figure 1):

1. A remote reference ground rod. Place the remote reference rod into the ground approximately 2 feet. It should be placed at a distance of three to four times the depth of any buried metallic structure connected to the service entrance neutral (i.e. 24 to 32 feet away from an 8-foot driven ground rod). For grounded metal objects that are deeply buried, such as well casings, field experience has shown that a distance of 150 feet away is usually satisfactory. If the remote reference ground rod is positioned as indicated it should measure within 5% of the primary neutral to true earth voltage, as derived from a primary profile. The same remote reference ground rod should be used for all reference ground measurements.
2. A connection to the primary neutral grounding electrode, usually on the conductor from the primary neutral to the primary neutral grounding electrode.

3. A connection to the ground bus in the service entrance panel supplying power to the animal confinement area.
4. A connection to the metallic structure(s) which the animals contact in their normal daily experience (typically the watering bowls, troughs, feed bunks, stanchions etc.).
5. A connection to the floor or earth on which the animal stands. This must be within 5 feet of the previous connection.

When testing service entrance panels not supplying power to animal confinement areas, connections 4 and 5 are replaced with a connection to the ground bus in the service entrance panel being tested. Other areas of concern for proper monitoring are entrances to animal confinement buildings having electric service (e,g, calf sheds) or other locations where a step potential may occur (e.g. feed lots, loafing areas).

DEFINITION OF TERMS

TERM	DEFINITION	UNITS
Ic	Current likely to flow through an animal in contact with Vc	A
Is	Net current imbalance on the secondary system due to 120 volt loads	A
Isn	Current flow on the secondary neutral conductor	A
Ip	Current flow on the primary neutral conductor	A
K	Ratio of animal contact to secondary neutral-to-earth voltage (K = Vcr/Vs)	
Ra	Resistance of shunt resistor used to simulate animal resistance (500 Ω)	Ω
Rp	Resistance of primary neutral-to-earth	Ω
Rf	Resistance of secondary neutral-to-earth	Ω
Rs	Source resistance of animal contact location	Ω
Rsn	Secondary neutral resistance	Ω
Vc	Animal contact voltage measured without shunt resistor in place	V
Vcr	Animal contact voltage measured with shunt resistor in place	V
Vp	Primary neutral-to-earth voltage	V
Vps	Secondary neutral voltage drop	V
Vs	Secondary neutral-to-earth voltage	V
$\mathbf{V^p_s}$	Contribution to secondary neutral-to-earth voltage by the primary system	V
$\mathbf{V^s_s}$	Contribution to secondary neutral-to-earth voltage by the secondary system	V
$\mathbf{V^p_p}$	Contribution to primary neutral-to-earth voltage by the primary system	V
$\mathbf{V^s_p}$	Contribution to primary neutraI-to earth voltage by the secondary system	V
$\mathbf{V^p_c}$	Contribution to animal contact voltage by the primary system	V
$\mathbf{V^s_c}$	Contribution to animal contact voltage by the secondary system	V

RATIO OF ANIMAL CONTACT VOLTAGE TO SECONDARY NEUTRAL-TO-EARTH VOLTAGE

Measurement of the source resistance is absolutely required to assess the quality and strength of animal contact voltage source and to calculate the amount of current likely to flow through an animal. A discussion of the importance and measurement of source resistance is presented in Appendix B. The animal contact voltage, Vc, will usually be less than the secondary neutral-to-earth voltage, Vs. The first test to be performed is the measurement of the ratio between animal contact and secondary neutral-to-earth voltage, the so-called K-factor. (K = Vcr/Vs).

Field experience has shown that K is usually between 20% and 80% but in unusual cases can range from as low as 4% to as high as 100%. The value of K is the same for both "off-farm" and "on-farm" sources. If any physical or electrical changes are made in the primary or secondary systems, testing must be repeated and the value of K recalculated. The K-factor should remain constant during testing unless grounding or source resistance changes. After determining the value of K, animal contact voltage readings can be referenced to Vs. Measurements of Vp and Vs should be made without a shunt resistor (open circuit). Measurement of animal contact voltage, Vc, should be made both with and without a shunt resistor to determine the source resistance, Rs. All subsequent recording of Vc should be with the shunt resistor in place.

PRIMARY AND SECONDARY NEUTRAL-TO-EARTH VOLTAGE

Neutral-to-earth voltages result from current flow through the resistances of the grounded neutral system. Neutral currents result from unbalanced 120-volt loads on the farm plus any primary neutral currents returning to ground through the parallel service entrance ground bus pathways. Primary and secondary neutral to earth voltages can originate from:

1. The off-farm primary neutral voltage drop associated with all loads and/or ground fault currents not originating from the specific load served by the transformer feeding the service entrance being evaluated.
2. Primary neutral and secondary neutral voltage drops associated with loads and/or ground fault currents originating from the particular service entrance being evaluated.
3. Primary neutral and secondary neutral voltage drops associated with loads and/or ground fault currents from those loads served by the transformer but originating from service entrances other than the particular one being evaluated.

All service entrances must, therefore, be de-energized except for the one being tested. The most common area of concern is the service entrance supplying power directly to animal confinement areas. For all other service entrances that do not supply power directly to animal confinement areas, one must perform measurement to determine the secondary neutral voltage drop and the contribution of that service entrance to the particular secondary neutral-to-earth voltage of the service entrance supplying power directly to the animal confinement area. A secondary neutral voltage drop test, Vps, should be done for each service entrance on the farm to determine any potential contribution to Vp, Vs and Vc from the other services on the farm. It is extremely important to note that Vps may be either in-phase with (adding to) or out-of-phase with (subtracting from) Vp.

240-VOLT LOAD TEST

Turn off all on-farm loads for this test. This may be done by opening the yard pole disconnect switch or by turning off all main breakers serving farm loads. Any voltages measured in the animal contact areas with no farm load on must therefore be due solely to contribution of the primary neutral.

If only 240-volt loads are operating on the farm, Vps will be strictly due to current from the primary neutral going to earth through the grounding structures on the service entrance grounding bus. No 120-volt loads should be operational during this test. It is recommended that a two stage 240-volt resistive load box of 75 amperes to 100 amperes total capacity be used for this test. A convenient place to connect this 240-volt load is to the line side of the secondary main disconnect unit with all farm load off. Record Vp, Vs, Vps, Vc, Ip (or the 240 volt load current), Ipn, and Isn during this test. Always check for unexpected 120-volt load current on the secondary neutral that may be due to faulty equipment, unintentional 120-volt loads, etc. If, and only if, no secondary neutral current from 120-v. loads exists, all of Vs is due to primary neutral contribution. Use the measured values of Vp, Vs, Vps, and Isn taken during the 240-volt load box test to determine Rp and Rf using the following equations:

$$R_f = \frac{V_s}{I_{sn}} \qquad (1)$$

$$R_p = \frac{V_p}{\frac{I_{LB}}{\text{xfmr ratio}} - I_{sn}} \qquad (2)$$

120-VOLT LOAD TEST

Turn the farm power back on. Operate a known and heavy 120-volt load (e.g. a hair drier or paint peeler) on one circuit while leaving all other farm loads off. Measure the secondary neutral voltage drop Vps, along with Vp, Vs and Vc with this known 120-volt load operating. It should be noted that Vps may be in-phase or out-of-phase with Vp. Use a clamp-on ammeter to measure the current flow in the secondary neutral conductor, Isn, connecting the transformer to the secondary grounding conductor. Use the values of Vps and Isn to calculate the resistance of the secondary neutral conductor and connections, Rsn.

The expected resistance of the secondary neutral conductor can be determined from the type and length of the secondary neutral conductor in consultation with a wire table. The value determined from a wire table should be close to the measured value of Rsn if the connections and conductor are both in satisfactory condition. If they differ markedly, a poor connection or some other undesirable condition may be indicated.

COMBINED 240- AND 120-VOLT LOAD TEST AND CALCULATION OF VOLTAGE CONTRIBUTIONS

This test is performed with the farm connected to the primary system and both the 240-volt load box and 120-volt load operational. Use the resistance values determined for Rp and Rf during the 240-volt load test and Rsn during the 120-volt load test in the following formulas. These resistance values may also be rechecked during this test.

Use the values of Vp, Vs and Vps measured during the combined 240-volt and 120-volt load tests in the following equations to determine the contributions of primary "off-farm" and secondary "on-farm" sources to the animal contact voltage. The development of the equations is presented in Appendix A.

$$V_s^p = \frac{V_p R_f + V_s R_p}{R_{sn} + R_p + R_f} \qquad (3)$$

$$V_s^s = \frac{V_s(R_{sn} + R_f) - V_p R_f}{R_{sn} + R_p + R_f} \qquad (4)$$

$$V_c^p = K V_s^p \qquad (5)$$

$$V_c^s = K V_s^s \qquad (6)$$

$$\frac{V_s^p}{V_s^s} = \frac{V_c^p}{V_c^s} = \frac{V_p R_f + V_s R_p}{V_s(R_{sn} + R_f) - V_p R_f} \qquad (7)$$

REFERENCES

USDA,1991. Agriculture Handbook No.696. "Effects of Electrical Voltage/Current on Farm Animals: How to Detect and Remedy Problems." U.S. Government Printing Office. A. Lefcourt, Editor, 1991.

APPENDIX A DEVELOPMENT OF EQUATIONS

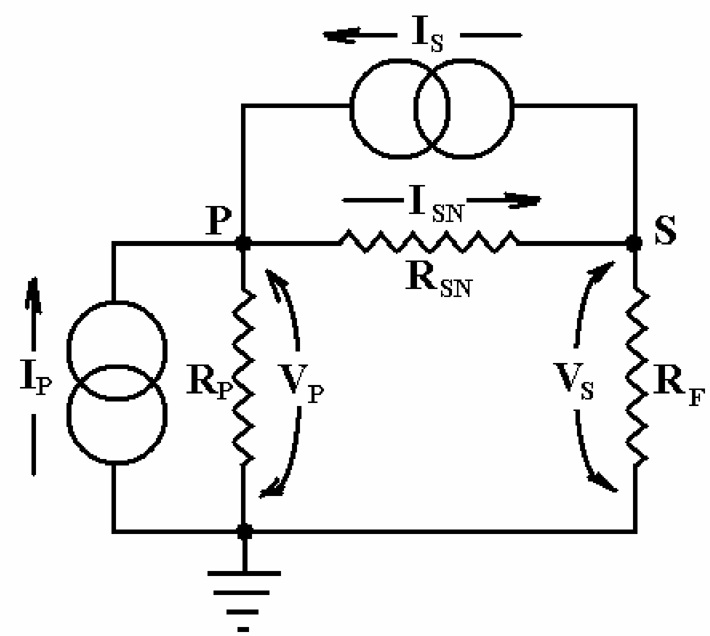

Figure 2: Circuit diagram for developing contributory equations.

Using Kirchhoff's current law at node P:

$$0 = I_p + I_s - \frac{V_p}{R_p} - \frac{V_p - V_s}{R_{sn}} \qquad \text{(A1)}$$

And again at node S:

$$0 = -I_s - \frac{V_s}{R_f} + \frac{V_p - V_s}{R_{sn}} \qquad \text{(A2)}$$

Solve A2 for I_s:

$$I_s = \frac{R_f V_p - R_f V_s - R_{sn} V_s}{R_{sn} R_f} \qquad \text{(A3)}$$

Substitute A3 into A1 and solve for I_p:

$$I_p = \frac{R_f V_p + R_p V_s}{R_p R_f} \qquad \text{(A4)}$$

Determine V_s and V_p due to I_p only:

$$V_s^p = I_p \left| \frac{R_p (R_{sn} + R_f)}{R_{sn} + R_p + R_f} \right| \left| \frac{R_f}{R_{sn} + R_f} \right| \qquad \text{(A5)}$$

$$V_p^p = I_p \left| \frac{R_p (R_{sn} + R_f)}{R_{sn} + R_p + R_f} \right| \qquad \text{(A6)}$$

Substitute A4 into A5 and A6:

$$V_s^p = \frac{V_p R_f + V_s R_p}{R_{sn} + R_p + R_f} \qquad \text{(A7)}$$

$$V_p^p = V_s^p \left| \frac{R_{sn} + R_f}{R_f} \right| \qquad \text{(A8)}$$

Determine V_s and V_p due to I_s only:

$$V_s^s = -I_s \left(\frac{R_{sn}(R_p + R_f)}{R_{sn} + R_p + R_f} \right) \left(\frac{R_f}{R_p + R_f} \right) \quad \text{(A9)}$$

$$V_p^s = I_s \left(\frac{R_{sn}(R_p + R_f)}{R_{sn} + R_p + R_f} \right) \left(\frac{R_p}{R_p + R_f} \right) \quad \text{(A10)}$$

Substitute A3 into A9 and A10:

$$V_s^s = \frac{V_s(R_{sn} + R_f) - V_p R_f}{R_{sn} + R_p + R_f} \quad \text{(A11)}$$

$$V_p^s = -V_s^s \frac{R_p}{R_f} \quad \text{(A12)}$$

APPENDIX B SOURCE RESISTANCE

When making stray voltage measurements, a determination of the source resistance of the circuit is vitally important because it indicates the effectiveness or strength of the animal contact meter connections and provides insight into the quality or efficacy of the voltage being measured. The strength of the voltage source to the animal contact area will dictate its ability to deliver current to the animal.

Stray voltage source resistance, Rs, is the total resistance from the animal to the voltage source both on the source side (flowing to) and on the return side (flowing away) of the animal. This includes contact resistance from hooves to floor, the bulk resistance of the concrete or soil floor, the resistance of the soil beneath the entire animal contact area, and the resistance of the total electrical system path (outgoing and returning) from the voltage source including both the farmstead and the utility electrical systems to the animal contact location.

Poorly made meter connections will result in incorrect voltage measurements (usually understating them) and the animal current calculated from these measurements. Ensuring a good (i.e. low resistance) animal contact meter connection and determining the source resistance will help to produce consistent and repeatable animal contact voltage measurements and produce an accurate diagnosis of any stray voltage concerns.

In the barn environment there are many factors that can and will affect source resistance. It is common for the stray voltage investigator to find loose or corroded connections in the barn metal work, poor code-required bonding between the electrical system and the metallic water system, corroded stanchion pipes, rubber animal comfort mats, and straw or other bedding material with high resistance in the stall areas. These factors and conditions such as soil moisture content may change with time resulting in varying source resistance and therefore varying animal contact current.

The investigator should attempt to make stray voltage measurements under both the “as-found” condition as well as a purposely contrived “worst-case” condition. The investigator should first determine the existing level of animal contact voltage and source resistance prior to making any modifications to the electrical system. A “worst-case” scenario can then be created by modifying the electrical system (bonding, etc.) to obtain the lowest possible source resistance. Measurements taken with the lowest possible source resistance will produce the highest possible animal currents, ensuring mitigation decisions will be made in the proper context.

A 4-inch square copper plate with pressure applied via a jack post or heavy dead weight will produce a reliable and repeatable contact point on a concrete floor for the rear hoof portion of the animal contact measurement. The concrete should be cleaned and free of all debris. A paper towel wetted with a brine solution should be placed first under the freshly cleaned copper plate. It is recommended that the copper plate be at least 18 inches from points where any stanchions, metal barn posts or other metal objects enter the concrete floor.

The other animal contact point for a stray voltage measurement should be made at the metallic water cup, front part of the stanchion or the water line. The surface chosen should be scraped free of all dirt, corrosion and debris. The meter lead should then be solidly connected to the metal via a clamping device that, when tightened, bites firmly into the metal surface.

In order to measure the strength of the voltage source when taking animal contact readings, a shunt with known or measured value (usually a nominal 500 Ohms which represents the average body resistance of a mature cow) is used. When measuring stray voltage levels, the resistor is connected across the high input impedance meter input terminals to reflect the voltage potential that causes current to flow through the animal.

To determine the source resistance, one must make two animal contact voltage measurements: with the shunt in place and without the shunt in place. It is assumed the meter has an input impedance greater than 1 MegOhm. The two readings should be taken as quickly in time as possible to lessen a chance of change in source voltage or resistance. The source resistance can then be calculated as follows:

$$\mathbf{Rs = Rsh\ ((Vc - Vcr)/Vcr)}$$

Where:
Rs = Source resistance
Rsh = Shunt resistance
Vc = animal contact voltage without **Rsh**
Vcr = animal contact voltage with **Rsh**

If the difference between the animal contact voltage with and without the shunt resistance in place is large, the value of the source resistance will be large. Extensive field measurements have shown that the normal range to be expected for source resistance is in the range of 100 to 500 Ohms. A source resistance of greater than 500 Ohms indicates poor connections to the measurement points or may actually reflect an accurate condition of high source resistance (e.g. inadequate water system bonding or a capacitively-coupled voltage source). If this protocol for setting up the animal contact measurement is followed and Rs is still above 500 Ohms, recheck all connections. If Rs is still too high, the strength of the animal contact current will be understated. One can consider improving various bonds, as described below, in the animal's environment to reduce Rs. Finally, if Rs remains above 500 Ohms, it may indicate that the voltage source is and will remain fairly weak.

Bonding of the water cups, water pipeline, stanchion and the secondary neutral of the farm's electrical system will usually reduce Rs and produce a higher animal contact current. Bonding can be done quite easily on a temporary basis by running a jumper wire from the metal work in the proximity of the animal contact area to the secondary neutral strip in the panel that feeds electricity into the animal contact area or to a location closer where the bonding to that neutral is already stronger. Making this modification will ensure that you have the required electrical system bonding and are making worst-case animal contact measurements. Always remember that there are consequences for making such modifications to the voltage source pathway such as lowering the source resistance for all animal contact areas and therefore increasing the available animal contact currents.